# 2. SCIENCE DRIVERS FOR THE RENEWAL

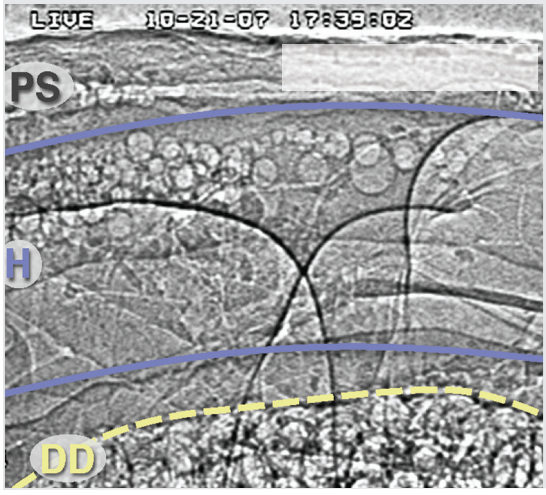
## 2.1 IMAGING AND COHERENCE

Roger Tsien, winner of the 2008 Nobel Prize in Chemistry for his discovery of green fluorescent protein labeling, stated in an opinion piece entitled "Imagining imaging's future" (Tsien 2003) that "Imaging specific molecules and their interactions in space and time will be essential to understand how genomes create cells, how cells constitute organisms and how errant cells cause disease. Molecular imaging must be extended and applied from nanometre to metre scales…" What Tsien believes is needed for biology is also true of the physical sciences. At the 2009 Spring meeting of the Materials Research Society there were several symposia specifically focused on complex hierarchical materials: "Three dimensional architectures for energy generation and storage," "Synthesis of bio-inspired hierarchical soft and hybrid materials," and "Architectured multifunctional materials."

X-ray imaging, especially with higher energy x-rays (20 kV and above), offers unique tools to address the critical issues of hierarchically structured systems. High-energy X-radiation penetrates through significant thicknesses of materials, for example, the entire active region of a semiconductor device, a small animal, or a sheet of structural alloy steel. Combined with high brightness at APS, this also enables the observation of fast and ultrafast processes as they are occurring, including fuel sprays, magnetic switching, and living organisms *in-vivo* (fig. 2.1.1). Images can be obtained using different contrast mechanisms, revealing light or dense elements, magnetic domains, or electric polarization for example. With improved -ray optics such as we are planning for the renewal, and new beamlines, we can image from the scale of nanometers to fractions of a meter. And through diffraction, scattering, and spectroscopy the lower end can be pushed down to the atomic level. Thus, x-ray imaging is the only tool that can encompass the many decades of length scales relevant to the control and understanding of hierarchical structures. Furthermore, hard x-rays are less damaging for thicker samples than soft x-rays and have greater elemental sensitivity because of increased fluorescence yield.

**"Imaging specific molecules and their interactions in space and time will be essential to understand how genomes create cells, how cells constitute organisms and how errant cells cause disease. Molecular imaging must be extended and applied from nanometre to metre scales…", Roger Tsien**

Phase contrast x-ray imaging, which requires excellent coherence in the delivered x-ray beam and favors a long beamline to increase spatial resolution and increase the coherent illuminated area, can visualize the internal structure of weakly-scattering objects, from insects (Socha

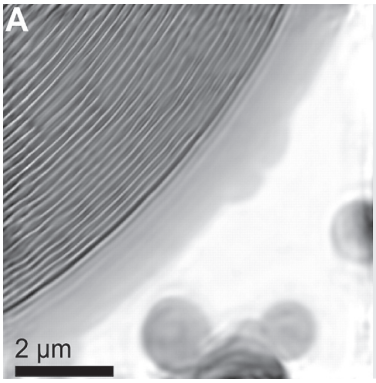



**Pumping blood**

***Fig. 2.1.1.*** *From an x-ray video of the beating heart of a grasshopper. The round structures are air bubbles, which are revealed only by phase contrast, and allow visualization of the flow of hemolymph (courtesy W.-K. Lee). Insects are of interest not just because they include almost 80% of all living species, but because micromechanical systems inspired by insect function have promise for biomedical drug delivery. APS renewal will allow imaging of much larger animals.*

et al. 2007) to fuel sprays (Wang et al. 2008). Reduced radiation dose results from the improved sensitivity of phase contrast compared with conventional absorption contrast imaging. An exciting new development in the imaging field is coherent diffraction imaging (CDI) and related techniques such as ptychography (Thibault et al. 2008) (fig. 2.1.2). By these methods lensless imaging, or enhancement of resolution beyond the limitations of conventional optical resolution, is possible. CDI is also attractive for "real materials under real conditions in real time" because optics need not be placed close to the sample.

Phase contrast imaging and related techniques have wide application, for example, in understanding the drying of cement (Allen et al. 2007), materials fracture (Drummond et al. 2005), electromigration in semiconductor devices (Lee et al. 2007), and magnetic domain switching (Jaramillo et al. 2007). Hard x-ray imaging has typically had relatively poor resolution compared with soft x-rays due to the difficulties of making zone plates, but that limitation is no longer true, and there is real promise for a <5 nm resolution hard x-ray microscope with substantial depth of field using Multi-Layer Laue lenses (Kang et al. 2006) (see fig. 6.3.1).




**Resolution extension**

***Fig. 2.1.2.*** *Using coherent illumination, the resolution of this x-ray image was extended [the original image did not resolve the outer zones of this zone plate (Thibault et al. 2008)]. A dedicated beamline in the renewal will allow resolution ~1 nm.*

Coherence is desired for imaging, but also for specialized scattering experiments. X-ray photon correlation spectroscopy (XPCS) exploits time correlations in the intensity of scattered coherent x-rays to characterize the dynamical behavior of samples (fig. 2.1.3). XPCS today addresses a unique combination of length and time scales for studying dynamics. Extending the spatio-temporal wndow will substantially expand the range of problems for study. In the renewal we will achieve an order of magnitude extension through a combination of improved source coherent flux, optics, and detectors.

A wide variety of complex fluids show structures with characteristic length scales that are in the few-tens-of-nanometers range and characteristic dynamics in the microsecond to millisecond range. Important examples of nanostructured complex fluids include mesophases of block copolymers and oil-water bicontinuous microemulsions that are stabilized by amphiphilic surfactants. In recent years, these sorts of phases have been the subject of intense interest, including detailed theoretical work focusing on their dynamics. Enhanced XPCS capabilities realized at a renewed APS to probe dynamics in this range of lengths and times will open new opportunities to investigate such materials. In polymer systems, despite the success of the concept of reptation in explaining many macroscopic properties, surprisingly few direct microscopic tests of reptation exist. Access to shorter times at a renewed APS will enable experiments that probe reptation in polymer melts on shorter length scales, thereby permitting critical examination of the reptation model for polymer dynamics.

X-ray imaging techniques are very powerful, but complementary to other methods. Transmission electron microscopy has extremely high resolution, albeit limited to thin specimens, whereas confocal optical microscopy can give rapid 3-D images of transparent objects. Users of the proposed x-ray bionononoprobe will benefit from *correlative microscopy*. As an example, a user could image

## Faster, smaller structural dynamics with XPCS

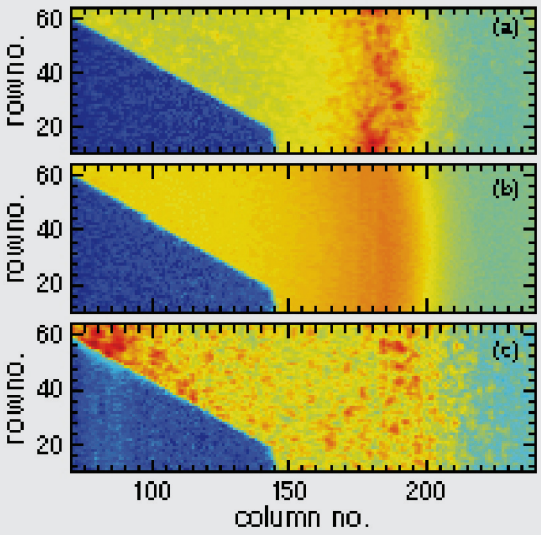



***Fig. 2.1.3*** *Access to dynamics at small length scales and short time scales makes XPCS valuable for studies of disordered materials, used for example in polymer processing of nanomaterials. The figure (Liu et al. 2008) illustrates averaged speckle patterns showing the relaxation in a model colloidal suspension as the strength of an attraction between the particles changes with temperature. (a) shows a repulsive glass at 33.00˚C; (b) the fluid phase at 33.39˚C; and (c) an attractive glass at 33.60˚C. The fluid is dynamic so that the speckle evident for the glass phase is washed out. The repulsive and attractive glasses are unusual. Important faster processes like polymer reptation, which have eluded study so far, could be accessed with a renewed APS.*

the time-dependent distribution of specific proteins in live cells by using optical microscopy. At a suitable time the specimen could then be cryo-fixed, and its trace metal content measured in 3D and correlated with the protein distribution. This capability will allow users to interrogate much more precisely the interaction between necessary intracellular metals and proteins. Beyond the direct scope of the proposal, we hope that the State of Illinois will fund an Imaging Institute which could house long x-ray beamline end stations together with complementary tools and expertise for correlative microscopy.

## Coherent diffraction imaging could unravel the structure of ligno-cellulose

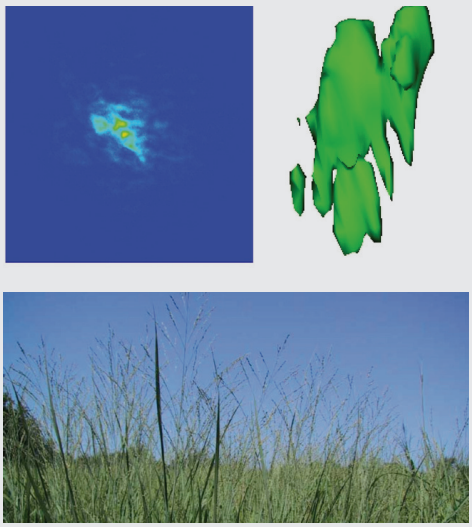


***Fig. 2.1.4****. A coherent diffraction image (left) and 3D reconstruction (right) of a cellulose nanocrystal about 300-nm size, embedded in corn stalk. The image is reconstructed through the technique of Bragg CDI (Robinson et al. 2009). These preliminary results could be expanded with dedicated CDI capabilities in the renewal to unravel the structure of ligno-cellulosic material. The aim is to optimize the structure through genetic engineering towards a more efficient route to production of renewable biofuels (courtesy L. Makowski). Switchgrass is a possible source of biomass for such applications.*

Plant cell walls are complex polymeric matrices of cellulose, lignin, and other materials that represent the bulk of biomass available for conversion to biofuels. The vast range of mechanical properties of plants –from switchgrass to oak trees– is a reflection of the wide variety of ways in which these constituents can be organized. The cellulose in these materials is arranged in crystalline fibrils that aggregate laterally to form microcrystals which are highly resistant to degradation. Understanding the form of these crystals and the effect that various processing steps have on them is of critical importance for optimizing the production of biofuels from biomass. Bragg CDI (Robinson et al. 2009) is particularly well suited to 3-D imaging of small nanocrystals in a large complex matrix (fig. 2.1.4). X-ray fluorescence imaging can be used to establish true elemental concentrations for a large number

of chemical elements, at trace level sensitivity. Additionally, the chemical state of elements can be probed and elemental information can be combined with phase contrast imaging (or CDI) to form uniquely revealing pictures of hierarchical structures. Due to the large penetration depth of hard x-rays, this is not confined to thin sections. This capability is especially important in biology and environmental science (fig. 2.1.5) but also in materials energy research (Buonassisi et. al. 2005).

**Viewing trace elements in 3D – a diatom that sequesters carbon**

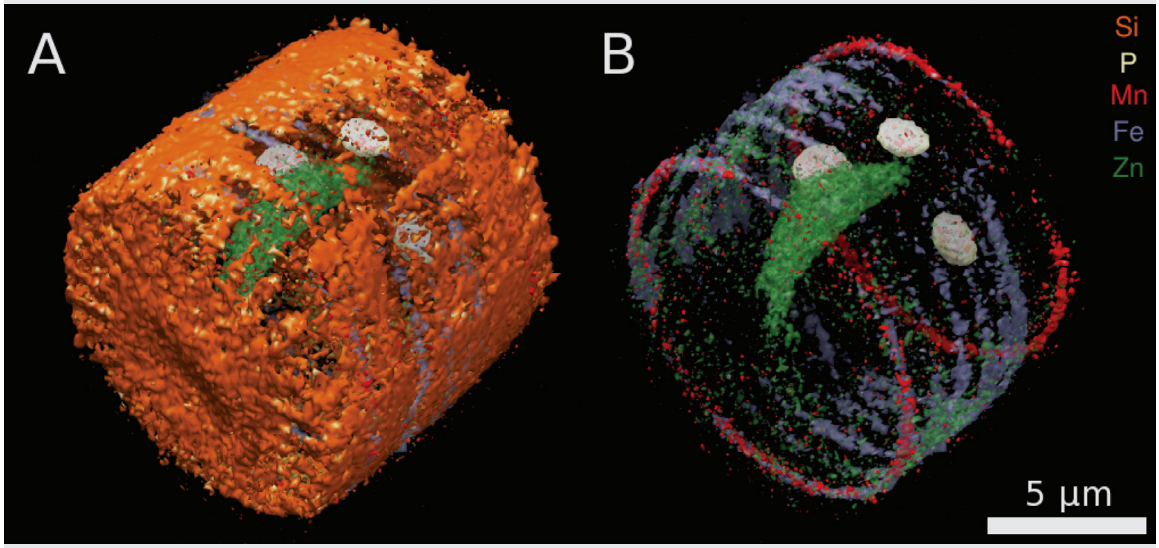



***Fig. 2.1.5.*** *Shown above are 3D renderings of trace elements in a freshwater diatom (Cyclotella sp.), with (A) and without (B) its dense siliceous cell wall. Diatoms play a key role in global cycles of bioactive elements, including carbon. The growth of diatoms in the ocean is often limited by Fe, which has led some to propose or test fertilizing the ocean with iron to stimulate diatom growth and thereby sequester more atmospheric carbon within the deep ocean (Coale et al. 2004). The exact role of diatoms in these cycles, and thus efficacy of such concepts, are poorly understood, but x-ray fluorescence microscopy is an extremely well suited tool to study elemental distributions in these cells (Twining et al. 2003). Using tomography, we can now determine the 3D elemental distribution, and elucidate the biological basis that underlies differences in elemental composition and the functional consequences of those differences. Ultimately, such knowledge could improve models that link ocean productivity to atmospheric composition and climate. To acquire these datasets, several techniques had to be brought together, involving a widespread collaborative effort. The APS renewal will allow acquisition of these datasets with much improved spatial resolution, elemental sensitivity, and speed through dedicated, improved instrumentation and improved source brightness. For example, specialized phase contrast detectors (Honberger et al. 2008) will allow reconstruction of specimen mass (de Jonge et al. 2008), as well as alignment of individual projections that have poor statistics.*

## 2.2 EXTREME CONDITIONS

Substances studied under extremes of pressure, temperature, magnetic or electric field can point to new high performance materials (figs. 2.2.1 and 2.2.2), or explain seismic activity. Historically, extreme conditions have proved a significant tool in improving the properties of materials that have important applications to energy and economic vitality, such as high-temperature superconductors and high-mobility semiconductors. Recent high-pressure science has shown surprising complexity

## Higher pressures

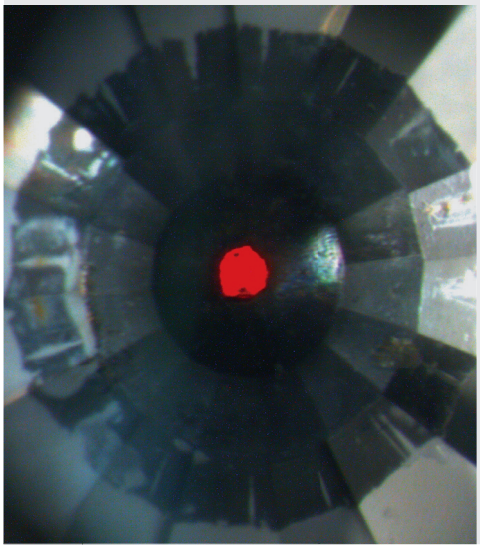


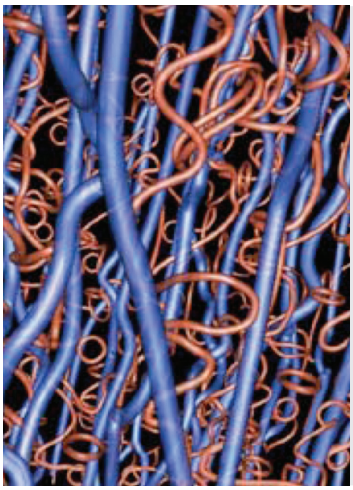
***Fig. 2.2.1.*** *Even simple materials can reveal surprises at extremes of pressure. Solid oxygen at 38 GPa displays a red color characteristic of the epsilon phase (Meng et al. 2008). At higher pressures oxygen becomes a metal and a superconductor on cooling.*

*Materials scientists desire higher pressures to explore new materials with new properties. Precise measurements under these conditions require that nanobeams be available at a renewed APS. High-flux, hard x-rays, and emerging techniques such as x-ray Raman inelastic scattering are essential to reveal the complex chemical bonding of light materials in pressure cells.*

and richness in the structure and properties of even simple elements such as sodium (Gregoryanz 2008; Ma et al. 2009). The highest known transition temperature for a superconductor has been obtained under pressure (Gao et al. 1994). Under pressure a colossal increase in ferroelectricity has been observed in $PbTiO_3$ (Wu et al. 2005). "Extreme magnetic fields especially affect the outer-shell valence electrons that control insulating, magnetic, conducting and superconducting behavior through their strong correlations" states a recent report (BESAC 2007). It is imperative to note that extreme conditions are created in small volumes, in containments that lead to strong attenuation of x-rays with limited angular access. As such, the ability to obtain high-brilliance, high-energy x-ray beams of nanometer dimensions makes APS an ideal place to study extreme environments and reveal the structure, correlations, and dynamics of electrons, atoms, and spins.

Extreme conditions allow us to probe new properties of materials; test and strengthen our theoretical understanding and so address the grand challenge of materials by design; and understand the interior of our own and other planets. Pressure is the volume derivative of energy, so high pressure studies are important for revealing the equation of state. Synchrotron radiation studies have identified a post-perovksite phase of $MgSiO_3$, that is believed to explain the important D" seismic anomaly at the earth's core-mantle boundary (Hirose 2006). Among the topical problems in geophysics is the concept of a deep carbon cycle, coupling the atmosphere to the earth's interior, and impacting climate change and the options for carbon sequestration. Work at APS was the first to show, for example, that hydrocarbons could be formed at geological pressures from inorganic components (Scott et al. 2004).

High-energy synchrotron radiation has become an essential tool in the study of materials under extreme conditions. The APS has been amongst the most productive sources in these studies, leading to more than 55 papers in the high-impact journals *Nature, Science, PNAS,* and *Physical Review Letters* in the years 2006-2008, more than any other x-ray facility worldwide. But there is demand for new and improved techniques, and more access.



## Ultradense hydrogen

***Fig. 2.2.2.*** *Ultradense hydrogen has been predicted to exhibit a unique metallic superfluid phase (Babaev et al. 2005), which might be observable with the extended pressures and imaging resolution made possible by the renewal of APS.*

In the past decade, significant progress in high-pressure synchrotron research has been made in the study of charge and vibrational dynamics by spectroscopic techniques including inelastic x-ray scattering (section 2.5). These high-pressure techniques are particularly flux limited and will greatly benefit from the higher flux and more efficient detection made possible in the APS renewal.

Completely new regimes of phases of matter will become accessible through the use of nanobeams with higher flux, which are a major feature of the renewal. Such beams will probe more extreme conditions in smaller or less homogeneous samples. The impact of the proposed order-of-magnitude reduction in beam sizes is not limited to merely incremental improvements, but will greatly expand the range of questions that can be answered in static experiments. For example, precise single-crystal studies of high-pressure phases become feasible when beam sizes approach those of individual crystallites within a powdered sample. Even higher pressure conditions can be achieved for short periods of time in dynamic shock compression, also opening the important study of shock wave propagation in solids. Dynamic compression capabilities (utilizing high velocity impacts, high intensity lasers, and pulsed power generators), coupled with ultra-fast measurements facilitated by the renewal, represent the most versatile approach for achieving the widest range of thermo-mechanical conditions in a controlled manner. A beamline with dedicated dynamic compression capabilities would be the first of its kind at a third-generation high-energy synchrotron facility.

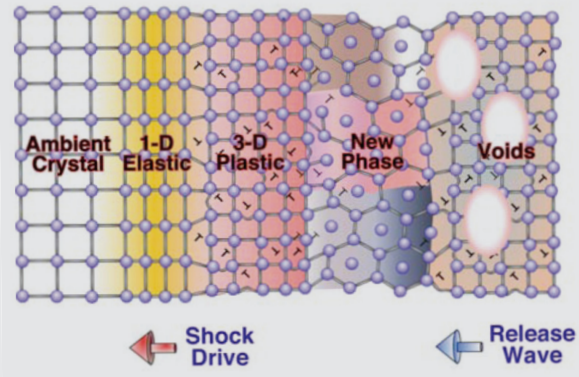


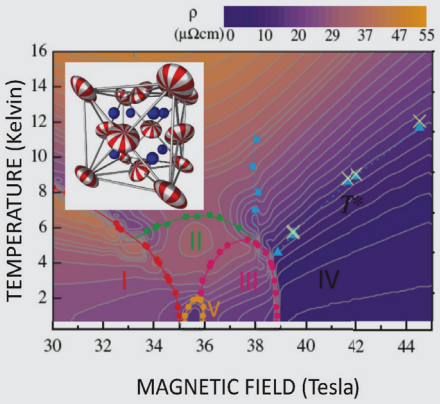

***Fig. 2.2.3**. Cartoon showing phenomena which can occur during shock deformation of a material, most of which have been predicted but not directly observed (courtesy H. Lorenzana).*

Shock deformation of materials occurs during materials failure and its understanding is important for stewardship of the nuclear stockpile. Novel, unexplored states of matter can occur at intense shock rates (fig. 2.2.3). Using intense focused beams from APS on small volumes permits more extreme conditions (e.g., pressures up to 500 GPa and temperatures up to 0.5 eV) to be attained with relatively simple equipment. At such pressures, localized electrons gain enough kinetic energy to mix with nearby valence and core electrons and create new phases of matter. Because of the interest in this capability from the DOE's National Nuclear Security Administration (NNSA), it has been separately proposed that a major part of the funding to build a dedicated shock compression beamline be provided by NNSA.

The magnetic field is a key fundamental parameter that enters directly into the energy expression (i.e., the so-called Hamiltonian) that governs all properties of materials. It is a contact-free experimental "knob" for tuning in novel phases that are of basic and applied interest. A dedicated beamline for application of high magnetic fields at APS has been recommended by a recent National Academy Study (COHMAG 2005) and is included in the renewal proposal. With the availability of high-magnetic fields (20-60 T) on a dedicated beamline, we may understand structure-property relationships in energy-related functional materials (multi-ferroics, shape-memory alloys, etc.), acquire insights into the mechanisms of high-temperature superconductivity, discover novel ordering phenomena and magneto-resistance pathways in complex magnetic systems for device applications, study the fundamental physics of of Bose-Einstein condensation in spin-gap compounds, and directly

*high-field instruments can unravel the nature of such phenomena (Paixao et al. 2002, Kim et al. 2003).*






manipulate synthesis of real materials *in-situ*. Both pulsed and continuous high-field magnets would be included in the beamline. A collaboration with the NSF's National High-Magnetic Field Laboratory could extend the capabilities to include a split-gap continuous field magnet reaching well beyond 30 T (fig. 2.2.4).

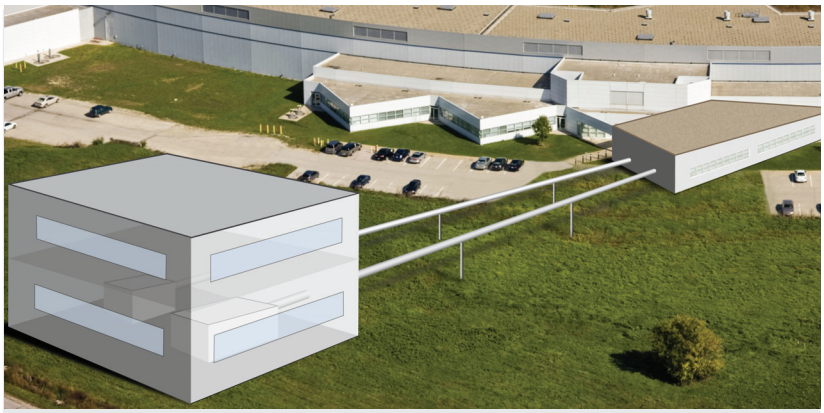
An exciting frontier is the combination of high pressures, temperatures, and electromagnetic fields. Compact high-pressure cells, for example, can be accommodated in ~20 T commercially available cryogen-free magnets. We would plan to provide support for experiments utilizing these instruments through an extension of the HPSynC (High Pressure Synergistic Center) capabilities. HPSynC is a jointly funded activity today at APS which supports high-pressure experiments beyond HP-CAT and GSECARS, which have traditionally been the leading beamlines for high-pressure science. HPSynC and similar groups could provide a mechanism to coordinate the development of new "extreme environments" around the entire APS ring, while supporting their implementation in the user program.

Extreme chemical environments that are also of great importance are covered in section 2.4, "Interfaces in complex systems."

# 4.1 IMAGING AND COHERENCE BEAMLINES

## LONG IMAGING BEAMLINES

To provide a large illuminated area with substantial coherence, needed for phase contrast imaging and related techniques, it is necessary to increase the length of a beamline beyond the space available within the experimental floor. The Advanced X-ray Imaging (AXI) beamlines at APS (fig. 4.1.1) will establish powerful new, dedicated x-ray imaging capabilities not currently available in the United States: a 200-m long undulator beamline for high-sensitivity wide-field-of-view x-ray imaging (WFI) and a long undulator beamline for coherent diffractive x-ray imaging (CDI). The WFI beamline will enable imaging at micrometer spatial and 100-ps temporal resolution, with a field size of a several centimeters. The large image field will greatly expand the



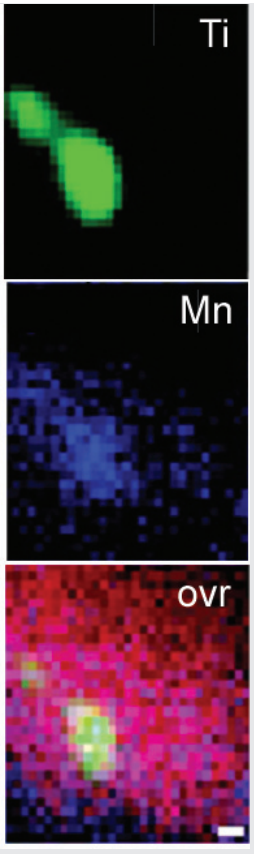
**Long beamlines planned for APS**

***Fig. 4.1.1****. Shown at sectors 19 and 20, which are well positioned for beamline extensions of ~ 200 m in length, together with a separately proposed Imaging Institute, which is being discussed with the State of Illinois as a matching contribution to the renewal project. The Institute could house the long imaging beamline end stations and complementary imaging capabilities and expertise. The only remaining open space adjacent to the experiment hall is shown at left and would be used for beamlines needing an external end station (e.g. dynamic shock compression and very high magnetic fields).*

size and types of animals and specimens that can be examined, leading to breakthrough research in evolutionary biology, physiology, medicine and agriculture. The 100 ps time resolution of the WFI beamline will support critical advances in engineering of materials and industrial products, with applications ranging from materials failure, to fuel injection technology, and fluid dynamics. The CDI beamline will be the first dedicated facility of its kind for nanometer resolution x-ray imaging of the interior of thick samples, buried structures, and interfaces with elemental, chemical, and magnetic state sensitivity. In complement to the larger length scales addressed by WFI, the CDI beamline will enable ground-breaking research at the nanoscale in the structural biology, materials, and condensed matter sciences, including intact eukaryotic cells and collagen fibers, domains and domain transport in magnetic and multiferroic systems, catalytic properties of nanomaterials and nanoparticles, and strain and defects in nanocrystals. The AXI beamline concepts capitalize on the enhanced capabilities of the APS planned for the renewal, such as brighter undulator sources and high-speed computer networks.

## BIONANOPROBE

The hard x-ray nanoprobe operated jointly with the Center for Nanoscale Materials has been highly oversubscribed with experiments from many scientific disciplines needing its 30nm resolution. Because of the importance of metals in cell biology, and the need for additional nanoprobe capacity and a specially-designed instrument for biological applications (including cryopreservation), a proposal for a "bionanoprobe" has been developed to address problems in the areas of bioremediation, climate change, biofuels, microbial interactions with contaminants, infectious and neuro-degenerative diseases, as well as novel nanovetor-based therapeutic drugs such as in fig. 4.1.2. Our understanding of diseases and of environmental contaminants is being significantly improved by our ability to image directly relevant metals in the context of tissues, single cells, and organelles. The possibility of resolving in yet more detail the specific interactions and motion of metals and contaminants at cell and vesicular membranes will lead to a yet greater understanding, with likely direct applications not only in areas such as bioremediation, microbial interactions with contaminants, and infectious and neuro-degenerative diseases, but also in climate-related studies (See also fig. 2.1.5.) .




### Targeting nanoconjugates within a cell

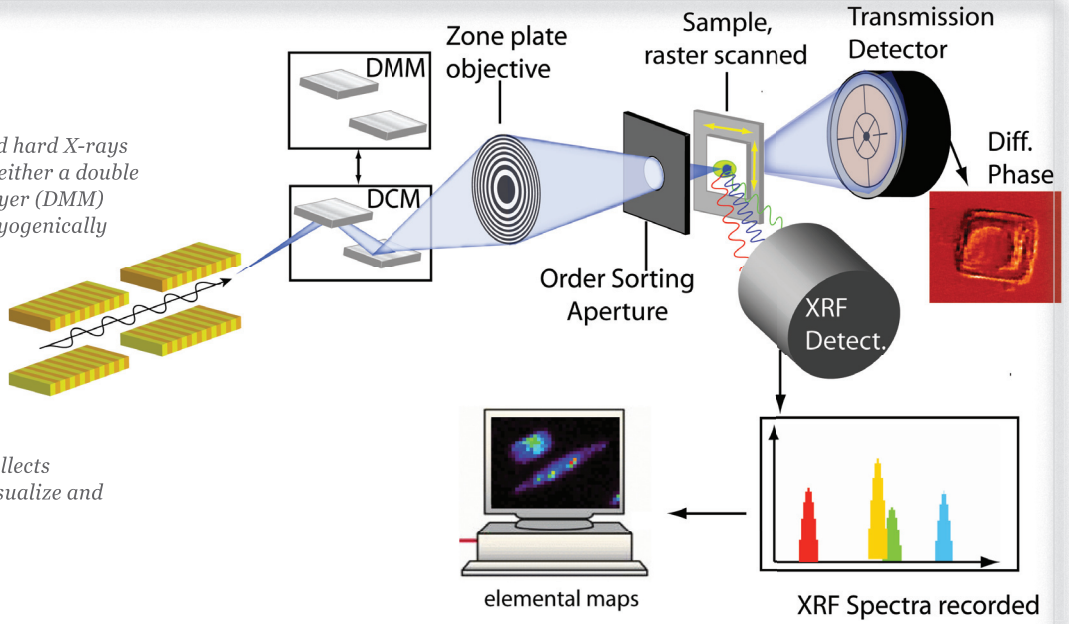
*Nanoconjugate targeting has significant biomedical potential, permitting localization of nanoparticle-bearing therapeutic and imaging molecules to specific cellular and intracellular sites.*

***Fig. 4.1.2.*** *X-ray fluorescence microscopy maps of single mitochondria inside a PC12 cell, 48 hours after it was transfected with mitochondria-specific nanoconjugates (Paunesku et al. 2007). From top to bottom: Ti (green, 0.04-1.76 μg/cm$^{-2}$), which shows the nanoconjugates; Mn, revealing the mitochondria (blue, 0.0 – 0.04 μg/cm$^{-2}$); and an overlap (ovr) map of Ti, Mn, and S (red). The scale bar is 300 nm. The bionanoprobe will improve the sensitivity and resolution of this important technique by more than ten fold, enabling study of smaller organelles.*

The bionanoprobe (fig. 4.1.3) will improve the achievable spatial resolution on soft specimens to 20 nm, and, crucially, provide a cryogenic sample environment for optimum specimen preservation. We expect an improved absolute sensitivity by >2 orders of magnitude (through higher spatial resolution and large-area multi-element x-ray fluorescence detectors), so that in

**Schematic view of the bionanoprobe**

***Fig. 4.1.3.*** *Undulator-generated hard X-rays will be monochromatized using either a double crystal (DCM) or double multilayer (DMM) monochromator. The sample (cryogenically preserved, in vacuum) is raster scanned through a 20-nm focus spot created by a Fresnel zone plate. A multielement silicon drift detector system records full x-ray fluorescence (XRF) spectra at each scan position; a dedicated segmented detector collects differential phase contrast to visualize and quantify specimen structure.*




ideal bio-specimens as little as 5-10 atoms will be detectable. Together with fast detector electronics, a dedicated differential phase contrast detector (for projection alignment), and the principle of dose fractionation, we will then be able to routinely image metal distributions in cryogenically preserved, whole, cells in 3D at ~20nm, within tens of minutes, as opposed to tens of hours.

## XPCS

We will upgrade out XPCS capabilities at sector 8 to realize specific gains in coherent flux as follows: a 4.8 m long undulator with a 2.7cm period (gain by a factor of 4), increased current (gain by factor of 2) and efficient vertical focusing (gain by a factor of 10) for a total gain of 80X. Users will also benefit from improvements in rapid correlation function data reduction that is a bottleneck for XPCS experiments. Importantly, the upgraded APS XPCS facility will be unique in being able to extend these same gains to higher x-ray energies that are out-of-reach at lower-energy (i.e. 3 GeV) sources to facilitate, for example, measurements of biologically relevant lipid layers under water and to reduce sample beam damage. Also, with respect to XPCS at future free-electron lasers (FEL's), the upgraded XPCS beamline at the APS will permit sample dynamics to be studied at the nanoscale in the physically important time scale spanning μs to ms. Because of the low repetition rates of FEL's and limitations on pulse delay lines, XPCS time scales accessible at the APS after the upgrade will complement those accessible at FEL's. The proposed upgrades will enable studies of dynamics within complex mesoscopically structured fluids and in biological systems, relevant to how small particles self-assemble into potentially useful structures. The dynamics of solid supported membranes, diffusion and surface fluctuations in free floating vesicles, and Brownian motion within concentrated protein solutions are examples which utilize higher-energy. Such studies will provide crucial insight into the central role of thermal fluctuations in biological activity at the cellular scale.

## COMPLEMENTARY IMAGING CAPABILITIES

We propose to expand capabilities in complementary microscopy tools (for correlative imaging) in collaboration with Argonne's Center for Nanoscale Materials (CNM) and the Electron Microscopy Center (EMC) and to use the Imaging Institute for additional laboratory space. Imaging is a major strategic direction for local universities, including the University of Chicago, Northwestern University, and the University of Illinois, and we have been planning joint activities with them. In particular, these institutions are strong in biomedicine, very relevant to a major application of our imaging tools in hierarchical systems. Specific instruments we would like to acquire include cryo-TEM and confocal optical microscopy, to supplement existing capabilities at CNM and EMC.